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On the influence of delamination on laminated paperboard creasing and folding

By Lars A. A. Beex and Ron H. J. Peerlings*

Department of Mechanical Engineering, Eindhoven University of Technology, PO Box 513, 5600 MB Eindhoven, The Netherlands

Laminated paperboard is used as a packaging material for a wide range of products. During production of the packaging, the fold lines are first defined in a so-called creasing (or scoring) operation in order to obtain uncracked folds. During creasing as well as folding, cracking of the board is to be avoided. A mechanical model for a single fold line has been proposed in a previous study (Beex & Peerlings 2009 *Int. J. Solids Struct.* **46**, 4192–4207) to investigate the general mechanics of creasing and folding, as well as which precise mechanisms trigger the breaking of the top layer. In the present study, we employ this modelling to study the influence of delamination on creasing and folding. The results reveal the separate role of the cohesive zone model and the friction model in the description of delamination. They also show how the amount of delamination behaviour should be controlled to obtain the desired high folding stiffness without breaking of the top layer.

Keywords: paperboard; creasing; folding; delamination; experimental mechanics; numerical simulation

1. Introduction

Laminated paperboard is an often used packaging material for products such as frozen foods, toys and shoes. Paperboard owes its wide use to its low price, its sustainability, the straightforward manufacturing process and its printability, which ensures appealing packages.

In order to appeal to customers, paperboard packages must be undamaged and have straight and undamaged folds. To obtain a fold with an undamaged top (outer) layer, the fold lines are defined by a creasing (or scoring) operation before folding. During this operation, the paperboard is pressed into a creasing channel by a creasing rule. As a result, the creasing zone of the paperboard is locally deformed. The creasing process is essential to avoid cracking of the top layer during folding, and thus, when studying the folding behaviour of paperboard, creasing must be considered as well.

Several studies have been performed to obtain insight into paperboard creasing and folding. In the study of Nagasawa *et al.* [1], the effect of crease depth and deviation of the creasing rule have been experimentally examined. Xia [2] has

*Author for correspondence (r.h.j.peerlings@tue.nl).

One contribution of 15 to a Theme Issue 'Geometry and mechanics of layered structures and materials'.

proposed a mechanical model for creasing and folding that includes complex and accurate material descriptions and delamination descriptions. Another mechanical model for creasing and folding has been proposed by Choi *et al.* [3], which includes the highly nonlinear material response of paperboard in the out-of-plane direction, as in the material model of Xia *et al.* [4]. The formulation of the delamination model used by Choi *et al.* [3] is however unclear. Nygårds *et al.* [5] have presented a mechanical model for creasing but the subsequent folding is not simulated.

In a previous study of Beex & Peerlings [6], the mechanisms that occur in paperboard during creasing and folding for different creasing settings have been demonstrated by means of experimental observations and numerical analyses of a mechanical model. Similar to the models of Xia [2], Choi *et al.* [3] and Nygårds *et al.* [5], the mechanical model uses a continuum description to predict the material response of the different paper plies, while a delamination description in between the different plies is used to describe the opening response of the plies relative to each other. Although more accurate material models for paper and paperboard have been proposed [4,7–9], the material model, which has also been used by Beldie [10], Barbier *et al.* [11] and Thakkar *et al.* [12] to model paper, was adopted in the model of Beex & Peerlings [6].

Here, we study in more detail the crucial role of delamination during creasing and folding using the mechanical model for a single fold line as proposed by Beex & Peerlings [6]. The mechanical model is ideally suited for this because its delamination description can easily be varied, while in experiments one is always limited in controlling the delamination patterns obtained. Moreover, experimental observations only give a limited mechanical insight, whereas in models all quantities of interest are readily available. The validity of the modelling results has been established by a detailed comparison with experimental results in Beex & Peerlings [6].

First, the role of delamination is investigated on the creasing and folding responses for standard industrial settings. Since the delamination description uses a cohesive zone model [13] and a friction model, the effect of the two separate components is also investigated for both processes. Furthermore, using a delamination strength of zero and a very high delamination strength, the two extremes are considered that mark the domain in which delamination is active. The mechanical model for creasing and folding is furthermore affected by the number of delamination surfaces used. The influence of this number is therefore investigated as well. Finally, a simplified mechanical model is considered, based on the experimentally obtained delamination pattern.

This paper is composed as follows. In §2, the creasing and folding experiments on a single fold line and the observations made in them are briefly summarized, with emphasis on the influence of delamination. In §3, the mechanical model for a single fold line as proposed by Beex & Peerlings [6] is briefly explained. In §4, the effect of delamination on the creasing and folding results is discussed. Finally, conclusions are presented in §5.

2. Creasing and folding experiments

A high grammage paperboard, with a thickness of 900 μm, is used in the experiments, because cracking of the top layer occurs most frequently for

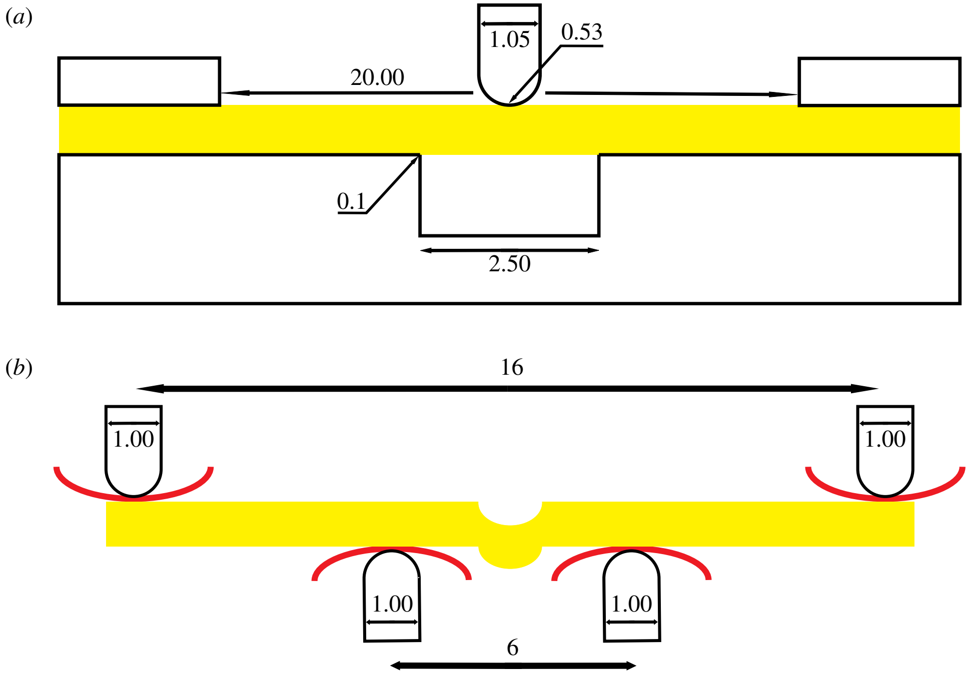

Figure 1. Sketch of the board sample placed (*a*) in the creasing tool and (*b*) in the folding tool after it has been creased. The grey (red online) curved lines between the sample and the four supports in (*b*) represent pieces of aluminium foil in the folding experiment. (Online version in colour.)

paperboard of a high grammage. The paperboard consists of a midlayer of 800 μm sandwiched in between a bottom and top layer, which both have a thickness of 50 μm. The midlayer is bulky and contains fresh-fibre mechanical pulp, while both outer layers are produced from chemical pulp containing virgin and recycled fibres and give stiffness and strength to the paperboard as a result of their compact structure. The observations from the creasing and folding experiments form the basis for the mechanical model and are also used to evaluate the modelling results. The focus is on one single fold line to obtain a case that is as simple as possible.

(*a*) *Experimental set-up*

Folds are made in paperboard samples perpendicular to the machine direction since breaking of the top layer occurs most frequently in this orientation. In the creasing and folding experiments, sample dimensions are used such that plain strain conditions are valid for the mechanical model. The experiments are performed at a temperature and humidity of 21–23°C and 15–30%, respectively. The velocities in the creasing and folding experiments are such that the strain rates have the same order of magnitude as in the experiments performed to characterize the material and delamination parameters [6].

During the creasing process, the paperboard is pressed into a creasing channel by a creasing rule until the creasing rule reaches the top of the creasing channel (i.e. the rule is displaced by 900 μm). A sketch of the experimental creasing set-up is shown in figure 1*a*. Two holders are used to hold the paperboard sample down but do not clamp it.

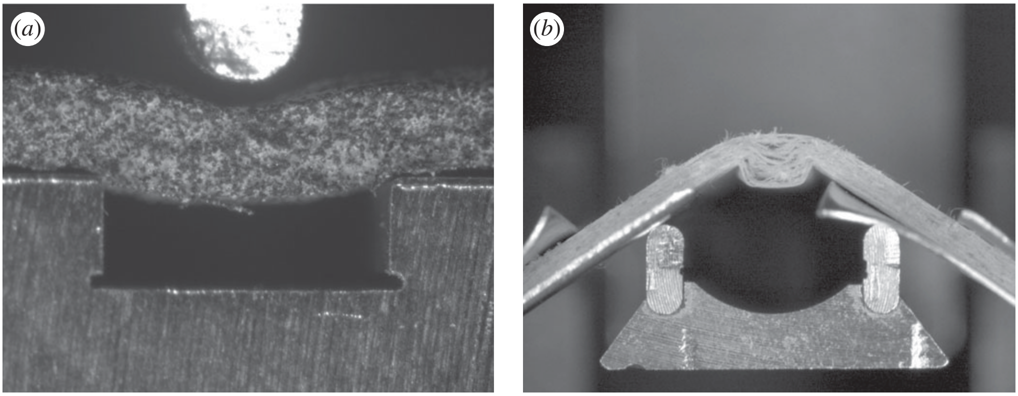

Figure 2. Microscopic images of (*a*) a board sample after the creasing test and (*b*) a sample during the folding test. A random pattern has been applied to the sample in (*a*) for optical strain measurement. Note also the aluminium foil between the sample and the supports of the four-point bending test.

A four-point bending experiment is used to test the folding response up to an angle of 90°. A benefit of this test is that it is rather insensitive to a misplacement of the creasing zone because the bending moment between both inner supports is constant. Thin pieces of aluminium foil are used to prevent the supports from indenting the samples. A sketch of the bending experiment is shown in figure 1*b*.

Both test set-ups are mounted in a micro-tensile stage so that the force as a function of the crease depth and the moment as a function of the folding angle can be measured. Furthermore, microscopic images are taken during both tests, which form the reference for the mechanical model.

(*b*) *Experimental observations*

Figure 2 shows two typical observations made during the experiments. A straightforward conclusion from figure 2 is that plastic deformation has occurred in the creasing zone during the creasing test as well as during the folding experiment. As shown in our previous study, plastic deformation of the creasing zone is necessary for a good fold line [6]. As indicated by Savolainen [14] and Xia [2], delamination is probably initiated in the shear regions during creasing, although it was not visible in our experiments. The simulation of the experiment, however, confirms that some delamination must have taken place—see §4. Furthermore, Savolainen [14] reports that in-plane tensile strains occur in industrial creasing operations, while they are not detected in our experiments. This is possibly caused by the fact that the holders do not clamp the sample whereas in industrial creasing the paperboard is more constrained.

During folding, the creasing zone shows multiple delaminations (figure 2*b*). Delamination occurs not only between the midlayer and the outer layers, but also within the midlayer itself. It is especially visible below the top layer in the centre of the creasing zone, but less delamination is present in the centre of the creasing zone between the lower plies. As a result of the multiple delaminations, the bottom plies can easily bend inwards while the in-plane tensile loading of

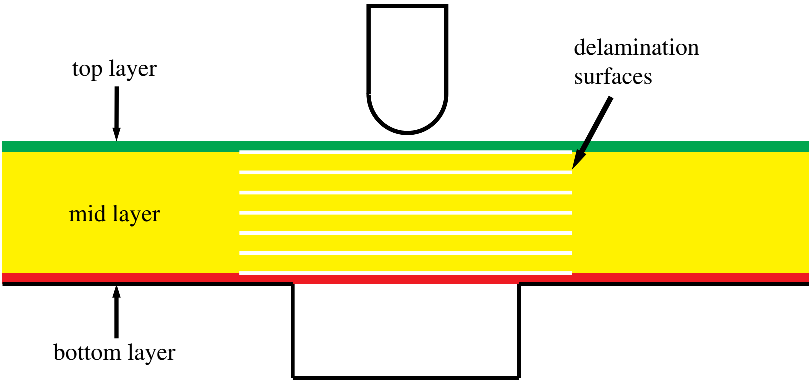

Figure 3. Schematic of the mechanical model of creasing. (Online version in colour.)

the top layer is such that the top layer remains intact. Although it is somewhat arbitrary, an average number of seven delamination surfaces has been observed in the creasing zone (which is important for the mechanical model). Nagasawa *et al.* [1] have observed similar delamination behaviour for thinner paperboards, but the number of formed plies differs.

More details about the experiments and experimental observations are presented in Beex & Peerlings [6].

3. Mechanical model

The mechanical model for a single fold line given by Beex & Peerlings [6] is used to investigate further the role of delamination on the creasing and folding mechanisms. The mechanical model consists of two main ingredients: a continuum description is used to model the material behaviour of the different plies of the paperboard; and a delamination description predicts the opening behaviour between the different plies during creasing and folding.

The two-dimensional (plane-strain) model is presented in figure 3. Seven delamination surfaces are used since this was the average number observed in the experiments. Although two delamination surfaces are present between the outer layers and the midlayer and five are modelled in the midlayer itself, the same delamination description and the same parameters are used for all delamination surfaces. The creasing tools and supports in the folding test are modelled as undeformable bodies, and the contact between the undeformable bodies and the sample is modelled as frictionless. The mechanical model has been implemented in a finite-element (FE) software (MSC.Marc) in which only half of the model is necessary owing to symmetry. The FE mesh uses 3508 bilinear elements and 3731 nodes. An incremental updated Lagrange approach was used that allows for large displacements and large rotations.

(*a*) *Material model*

The material description must allow for different responses in the different principal directions of the paper, which are caused by the preferred direction of the fibre network. The material description must furthermore be elastoplastic according to the experimental observations. The (hypo-)elastic behaviour of the material description therefore is orthotropic and Hill's yield criterion is used for the onset of yield. Isotropic strain hardening is used. The Jaumann objective stress rate is used in the FE software to preserve frame indifference. The use of only a few material parameters in the material description is beneficial for the experimental material characterization. The material model is used for all three paper layers, but its parameters are separately determined for every layer.

(*b*) *Delamination model*

The delamination description uses a cohesive zone model in combination with a friction law. The damage-based cohesive zone implementation of Van Hal *et al.* [13] is used. This formulation uses one parameter to distinguish between tangential opening and normal opening. Since Xia [2] reports that delamination occurs during creasing in regions with shear strains, the paperboard's opening response in the tangential direction is used to fit the traction–separation law. The characterization of the traction–separation law is non-trivial because a stack of bulk plies and delamination surfaces must be considered. Friction needs to be included because a higher traction is required for tangential opening if out-of-plane normal compression is present as well. Note that this stress state indeed occurs in the creasing process. A straightforward Coulomb friction model is used.

More detailed information about the material model, delamination model and the exact material characterization can be found in Beex & Peerlings [6].

4. Results

(*a*) *Reference case*

In figure 4*a*, the experimental and numerically computed force–crease depth curves are presented for creasing until 900 μm in a reference configuration of the experiment. The numerical and experimental curves match rather accurately. Note that the parameters of the material have been identified in separate experiments and the numerical curves are thus true predictions. The force–crease depth curve shows the mechanisms that occur during creasing in combination with the numerically computed creasing zone (figure 5*a*).

The curve starts linearly, indicating that only elastic deformation occurs initially (apart from a settling effect in the experimental data). At a crease depth of approximately 200 μm, the slope of the crease curve decreases owing to the onset of separation of the delamination surfaces. The numerically computed creasing zone (figure 5*a*) shows that delamination occurs during creasing. The fact that the slope of the predicted curve is smaller than that of the experimental curve is probably caused by the use of the same traction–separation response for all delamination surfaces. Incorporating some disorder in the delamination behaviour may result in a more gradual opening of the different surfaces, leading to an increase of the force–crease depth curve.

At a crease depth of approximately 650 μm, the slope of the crease curve starts to increase because the progress of delamination stops. The increase of the slope is caused by compression of the sample, which becomes more pronounced [6]. The

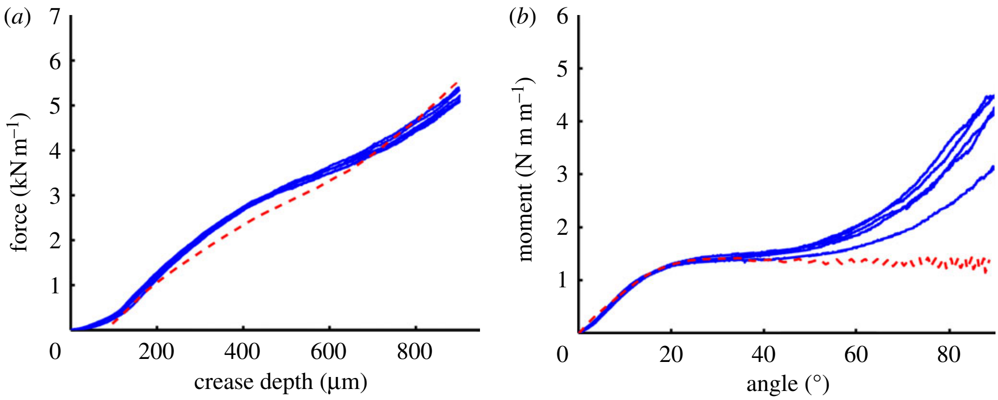

Figure 4. Experimental (solid line) and numerically predicted (dashed line) (*a*) force–crease depth curves of the creasing process and (*b*) moment–angle curves of the folding process for the reference case. (Online version in colour.)

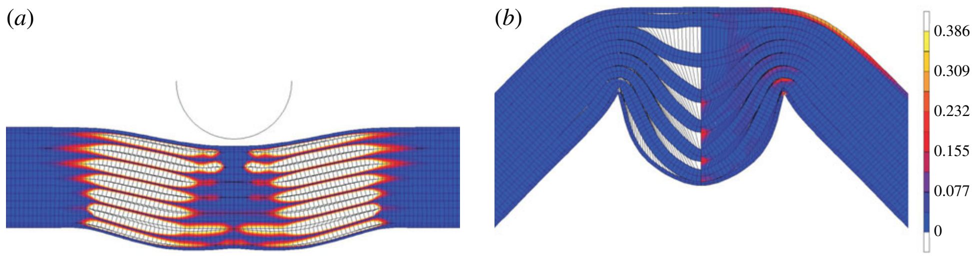

Figure 5. The computed creasing zone after (*a*) creasing to 900 μm and (*b*) subsequent folding. The grey zones indicate regions with separations larger than the effective separation in (*a*). In the left half of (*b*) the cohesive zone elements of the delamination surfaces are shown in white and in the right half the principal maximum strain is shown. (Online version in colour.)

overestimation of the stiffness at this depth is caused by the linearization of the out-of-plane response in the material model [6].

The predicted moment–angle curve of folding corresponds accurately to the experimental data up to an angle of 40° (figure 4*b*). For larger angles, the aluminium foil used in the experiments deforms substantially and the experimental data are therefore no longer reliable. The numerically predicted moment–angle curve oscillates for angles larger than approximately 60°. These oscillations have no physical meaning, because they are caused by the large rotation of the sample and the contact between the relatively larger elements at the end of the sample and the outer support.

The initial response during folding is governed by three mechanisms: the two top plies are stretched horizontally (figure 5*b*); and the lower plies bend away during the folding process. As a consequence, the delamination surfaces continue to open towards the middle of the creasing zone. The delamination surfaces continue to carry a small load after they have reached their maximum traction. This physically corresponds to a small number of fibres that bridge the delamination surfaces.

At an angle of 15°, the slope of the moment–angle curve decreases because all delamination surfaces have been opened beyond their maximum traction and therefore hardly contribute any more. The third stage starts at an angle of 25° when the top plies are completely stretched horizontally. The observed plateau therefore is mostly governed by the inward bending of the bottom plies.

At the end of folding, strain localization occurs in the top layer, indicating the location for possible breaking of the top layer. However, although the strains in the top layer are rather high compared with the breaking strains in uniaxial tension, in the experiments with the reference settings the top layer remained intact. This indicates that a complex stress state occurs in the top layer that influences the breaking strain of paper.

In the study of Beex & Peerlings [6], more results of the mechanical model for the reference case and variations from it are discussed.

(*b*) *Influence of delamination description*

To investigate the influence of different aspects of the delamination on a fold line, the same mechanical model is used, but the delamination model is adapted in a number of different ways.

First, the mechanical model is considered in which delamination is prevented completely. This is accomplished by setting the cohesive strength to a high value. The responses of this mechanical model during creasing and folding are represented by the dotted curves in figure 6. The crease curve remains almost entirely linear until the sample deforms plastically. Comparing it with the reference curve (dashed) shows the influence of delamination on the creasing response. Both responses start linearly but the standard crease curve starts to deviate when delamination starts. The subsequent bending response of the mechanical model without delamination is obviously stiffer (figure 6*b*) and leads to strong strain localizations in the top layer (not shown).

The dashed-dotted curves in figure 6 represent the responses of the mechanical model in which the delamination surfaces can freely open without any traction. This has been done by setting the cohesive zone strength and friction coefficient to zero. The initial crease response is much lower than the (dashed) reference response because the delamination surfaces open directly at the beginning of the creasing process. Furthermore, no distinct slope change of the crease curve can be observed around 650 μm, at which the curve of the reference model becomes steeper. This is also caused by the traction-free delamination surfaces that continue to open during the entire creasing process. As a consequence, no compression of the board is necessary to accommodate the rule displacement.

Proceeding to the folding response of the model with traction-free delamination surfaces (figure 6*b*), it can be observed that the initial slope of the response is smaller. This is caused by the missing traction for normal opening of the delamination surfaces, which is one of the three mechanisms that contribute to the initial stiffness for the standard model (see §4*a*). The traction-free opening of the surfaces ensures that the lower plies can easily bend inwards.

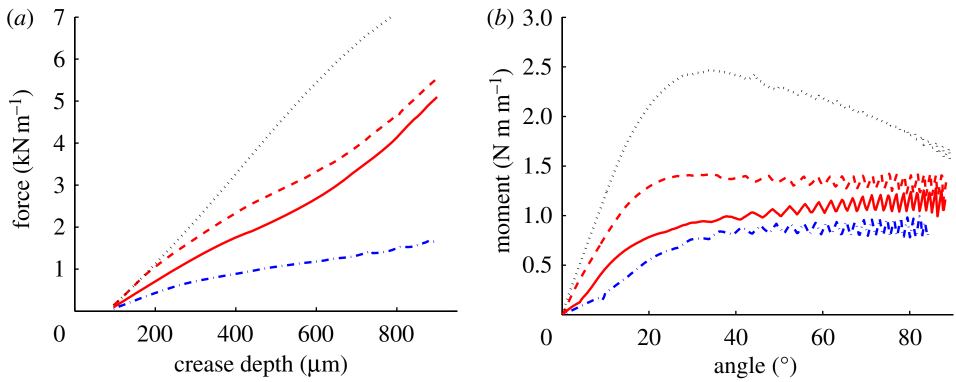

Figure 6. (*a*) The force–crease depth curves and (*b*) moment–angle curves of the original mechanical model (dashed line), the mechanical model without delamination (dotted line), the model with delamination surfaces that can open freely and slide without friction (dashed-dotted line) and the model in which the delamination description only includes friction and no cohesive zones (solid line). (Online version in colour.)

The results of the mechanical model in which only the friction is used, but no cohesive zone formulation, are represented by the solid curves in figure 6. Comparing the crease curve with that for the reference model, the influence of the cohesive zone formulation becomes clear. However, it is also interesting to compare the crease curve with that of the model in which not only the cohesive zone formulation but also the friction model (dashed-dotted in figure 6) is missing. From this comparison, the influence of friction during creasing becomes clear, which is of substantial importance to accurately model creasing.

If we compare the folding response of the model with only friction in the delamination description with the response of the standard mechanical model (figure 6*b*), it is clear that the bending responses deviate substantially more than the creasing curves. This difference is partially caused by a slightly different computed creasing zone after creasing (which forms the initial condition for the folding process). However, a larger effect is that friction only influences tangential opening, and therefore the influence of friction is rather small for the folding process because the delamination surfaces mostly open in the out-of-plane direction. As a result, the folding response is closer to the response of the mechanical model with traction-free delamination surfaces.

The creasing and subsequent folding responses of paperboard are clearly sensitive to the different aspects of delamination descriptions. Bounds on the creasing and folding data are given by the cases in which no delamination can occur (dotted curves in figure 6) and in which delamination is traction-free (dashed-dotted curves in figure 6). These bounds indicate the domain in which delamination is governing the mechanical response. Clearly, the domain is large and delamination is thus of substantial importance for creasing and folding. From these bounds and the responses in between them, it can be concluded that the influence of friction is relatively large during creasing owing to tangential opening under out-of-plane compression loading (caused by the creasing rule) and the effect of the cohesive zone description is more pronounced in the folding process.

(c) Influence of number of delamination surfaces

The use of seven delamination surfaces in the mechanical model is somewhat arbitrary. A mechanical model with six delamination surfaces (four within the midlayer and two between the midlayer and the two outer layers) is analysed to investigate the influence of the number of delamination surfaces on the creasing and folding curves. The traction–separation law of the cohesive zone description is re-established according to the characterization procedure described by Beex & Peerlings [6]. This ensures that the opening responses of the different stacks in the pure normal and tangential directions are identical.

The force–crease depth curve and moment–angle curve are presented as dotted curves in figure 7. The responses hardly deviate from those of the reference model. During creasing, delamination starts at the same crease depth as for the reference model, but the slope decreases less, and at the depth at which delamination stops the slope also increases less. From this, it can be concluded that the influence of delamination is somewhat smaller during creasing than for the reference model, which is consistent with the fact that fewer delamination surfaces are used.

The moment–angle response of folding is almost identical to the folding curve computed with the reference model. This indicates that folding is less sensitive to the number of delamination surfaces than the creasing process, even if the creasing sets the initial conditions for folding. The cause is that separation of the delamination surfaces during folding occurs in the out-of-plane direction, for which the number of delamination surfaces in the mechanical model is apparently less important than for the tangential opening during the creasing process. Although the individual plies after separation are thicker for the model with six delamination surfaces compared with the reference model, this has no significant effect on the folding response. Apparently, the combined response of a smaller number of thick plies leads to almost the same behaviour as for the reference number of plies with the reference thickness. However, if the number of delamination surfaces is further decreased, it is questionable if the folding responses still match, because theoretically the bending stiffness of one ply scales cubically with the thickness of the ply.

(d) Shape of the creasing zone

Although the numerically predicted force–crease depth curves and moment–angle curves for the reference case correspond well to the experimental curves (figure 4), the predicted creasing zone after folding (figure 5*b*) is different from the experimentally obtained creasing zone after folding (figure 2*b*). In the numerical analyses, delamination occurs in almost the entire creasing zone, whereas in the experiments delamination is not observed in between the lower plies in the centre of the creasing zone. A mechanical model in which traction-free delamination is assumed in the shear regions in between the creasing rule and the sides of the creasing channel and perfect bonding at the centre of the crease is used to study the effect of this different delamination pattern. Note that this model is significantly simpler to implement, as it does not require cohesive zone elements and the data associated with them.

The creasing zones after creasing and after folding as predicted by the alternative mechanical model are shown in figure 8. Compared with the results of the reference model, a relatively large amount of plastic deformation has

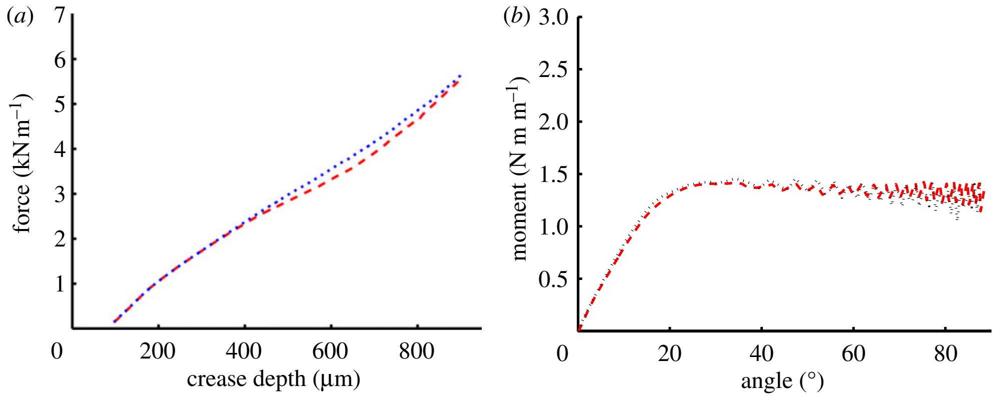

Figure 7. (*a*) The force–crease depth curves and (*b*) moment–angle curves of the reference model (dashed line) and the mechanical model with six delamination surfaces instead of seven (dotted line). (Online version in colour.)

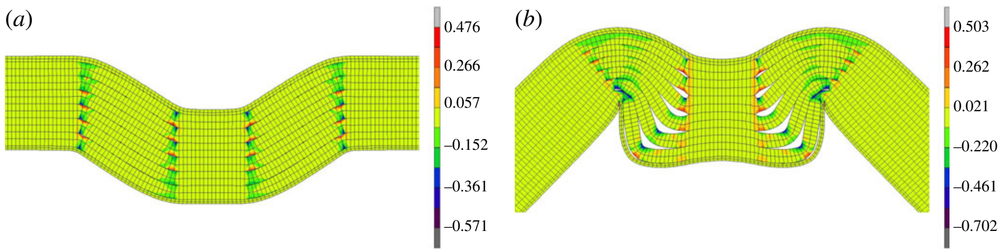

Figure 8. The predicted creasing zone (*a*) after creasing and (*b*) after folding for the mechanical model in which traction-free delamination surfaces are solely modelled in the shear regions between the creasing rule and the sides of the creasing channel and perfect bonding between the plies is assumed otherwise. The (colour) contours correspond to the major principal plastic strains. (Online version in colour.)

occurred during creasing. More interesting is the sample's shape after folding. The upper plies are permanently deformed into a curved shape, which does not match the experimental observation in figure 2*b*. This is caused by the fact that the delamination cannot progress towards the centre of the creasing zone during folding. However, the predicted deformation of the lower plies matches the experiments better than that of the reference model (figure 5*b*). This suggests that the out-of-plane opening behaviour of the delamination surfaces is not accurately modelled in the reference model, although it matches the out-of-plane normal tensile tests on paperboard well [6].

The moment–angle curve of this mechanical model deviates only moderately from the folding response of the reference model (figure 9), although the creasing zones after creasing and folding are rather different (figures 5 and 8). Whereas the shape of the experimentally obtained fold line is modelled more accurately, the predicted moment–angle response appears to deviate more from the experimentally measured one (compare with figure 4). This indicates that the

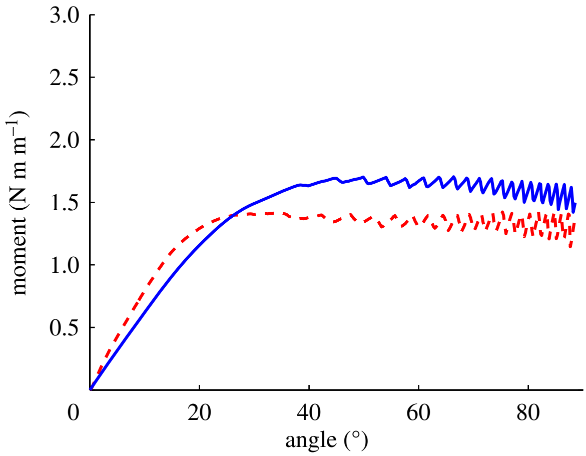

Figure 9. The moment–angle curves for the reference model (dashed line) and the mechanical model with traction-free delamination surfaces in the shear regions (solid line). (Online version in colour.)

moment–angle curves, which are used in the paperboard industry to evaluate the quality of a single fold line, are not sufficient to evaluate folds. Microscopic images in combination with moment–angle curves seem a better alternative to register fold line properties.

5. Conclusion

In this paper, the mechanical model proposed by Beex & Peerlings [6] for the creasing and folding of laminated paperboard is used to study the influence of delamination on the creasing and folding process. Two extreme cases considered are that in which no delamination can occur and that where the delamination is traction-free. The true creasing response is in between these extremes, indicating that some delamination occurs during creasing. The subsequent bending response is closer to the traction-free delamination case, which is also consistent with the presence of delamination after creasing.

The influence of the two components in the delamination description, the cohesive zone model and the friction model, is established by comparing the complete, reference model with a mechanical model in which only friction is included in the delamination description. From the results, it can be concluded that friction is the most important for creasing, and the cohesive zone model has the largest influence on the folding response. This is caused by the tangential opening of the delamination surfaces under normal compression during creasing and normal opening of the surfaces during folding.

Furthermore, it can be concluded that a higher cohesive zone strength leads to a stiffer folding response and the occurrence of a maximum in the folding response. This is desired in the paperboard industry because a high folding stiffness renders strong packages, and a maximum in the folding response characterizes desired plastic deformation of a fold line, so that the shape of paperboard boxes remains after folding. Unfortunately, the top layers of boards with such a folding response tend to crack easily during folding. For this reason, a delicate balance must be found in the desired characteristic folding response without breaking of the top layer. The delamination behaviour has a significant influence on this interplay, not only by the direct influence of the delamination description on the folding response, but also via its influence on the creasing process, which determines the initial configuration for the folding process. Therefore, if the delamination behaviour of paperboard can be altered, the desired folding response can be obtained.

Finally, a simplified mechanical model is built on the basis of the experimental observation of the creasing zone after folding. In the alternative mechanical model, traction-free delamination zones are inserted in the shear regions, whereas perfect bonding is assumed elsewhere. The predicted creasing zone after folding is quite different from the creasing zone predicted with the reference model, but nevertheless the moment–angle curves match relatively well. For this reason, this simpler model might be sufficient for the paperboard industry to obtain insight into creasing and folding characteristics.

References

1 Nagasawa, S., Fukuzawa, Y., Yamaguchi, T., Tsukatani, S. & Katayami, I. 2003 Effect of crease depth and crease deviation on folding deformation characteristics of coated paperboard. *J. Mater. Process. Technol.* **140**, 157–162. (doi:10.1016/S0924-0136(03)00825-2)

2 Xia, Q. S. 2002 Mechanics of inelastic deformation and delamination in paperboard. PhD thesis, Massachusetts Institute of Technology.

3 Choi, D. D., Lavrykov, S. A. & Ramarao, B. V. 2007 Simulation studies of delamination effects in the scoring and folding of paperboard. In *Proc. 61st Appita Annual Conf. and Exhibition, Gold Coast, Australia, 6–9 April 2006*, pp. 209–216. Carlton, Australia: Appita Inc.

4 Xia, Q. S., Boyce, M. C. & Parks, D. M. 2002 A constitutive model for the anisotropic elastic–plastic deformation of paper and paperboard. *Int. J. Solids Struct.* **39**, 4053–4071. (doi:10.1016/S0020-7683(02)00238-X)

5 Nygårds, M., Just, M. & Tryding, J. 2009 Experimental and numerical studies of creasing of paperboard. *Int. J. Solids Struct.* **46**, 2493–2505. (doi:10.1016/j.ijsolstr.2009.02.014)

6 Beex, L. A. A. & Peerlings, R. H. J. 2009 An experimental and computational study of laminated paperboard creasing and folding. *Int. J. Solids Struct.* **46**, 4192–4207. (doi:10.1016/j.ijsolstr.2009.08.012)

7 Stenberg, N. 2003 A model for the through-thickness elastic–plastic material behaviour of paper. *Int. J. Solids Struct.* **40**, 7483–7498. (doi:10.1016/j.ijsolstr.2003.09.003)

8 Castro, J. & Ostoja-Starzewski, M. 2003 Elasto-plasticity of paper. *Int. J. Plast.* **19**, 2093–2098. (doi:10.1016/S0749-6419(03)00060-3)

9 Isaksson, P., Hägglund, R. & Gradin, P. 2004 Continuum damage mechanics applied to paper. *Int. J. Solids Struct.* **41**, 4731–4755. (doi:10.1016/j.ijsolstr.2004.02.043)

10 Beldie, L. 2001 Mechanics of paperboard packages: performance at short term static loading. Licentiate dissertation, Lund University, Sweden.

11 Barbier, C., Larsson, P. L. & Östlund, S. 2004 On dynamic effects at folding of coated papers. *Compos. Struct.* **67**, 395–402. (doi:10.1016/j.compstruct.2004.01.025)

12 Thakkar, B. K., Gooren, L. G. J., Peerlings, R. H. J. & Geers, M. G. D. 2008 Experimental and numerical investigation of creasing in corrugated paperboard. *Phil. Mag.* **88**, 3299–3310. (doi:10.1080/14786430802342576)

13 Van Hal, B. A. E., Peerlings, R. H. J., Geers, M. G. D. & Van der Sluis, O. 2007 Cohesive zone modeling for structural integrity analysis of IC interconnects. *Microelectron. Reliab.* **47**, 1251–1261. (doi:10.1016/j.microrel.2006.08.017)

14 Savolainen, A. 1998 *Paper and paperboard converting*. Fapet Oy, Jyväskylä, Finland: Finnish Paper Engineers' Association.